

Improved Characterization and Monitoring of Moisture Associated With Atmospheric Rivers

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The accurate characterization of atmospheric moisture fields (including water vapor and clouds) is essential for improved forecasts of cool- and warm-season heavy precipitation events associated with Atmospheric Rivers (AR) and AR-like events observed around the world. Our experience with the AR Observatories established along the West Coast of North America has resulted in the development and implementation of new tools and techniques to quantify the characteristics of AR's at landfall, and new techniques to quantify observation errors and monitor the accuracy of satellite water vapor observations on landfall. More problematic is the verification of the accuracy of moisture observations and analyses over the open ocean that are needed to improve longer-range forecasts and warnings of heavy precipitation associated with landfalling AR's. This paper presents initial results from ongoing GPS-Met observations made from offshore oil production platforms more than 100 km offshore in the Gulf of Mexico that describe for the first time the error characteristics of satellite microwave TPW estimates.

1. Atmospheric Rivers

Atmospheric Rivers (AR's) are long narrow bands of moisture that transport energy in the form of latent heat poleward from the Equatorial Warm Pool (**Figure 1**). AR's are usually confined to the warm sector of extratropical cyclones which form along the leading edge of cold fronts (Zhu and Newell 1998, Ralph et al. 2004, Bao et al. 2006, and others). This phenomena was also referred to as the "warm conveyor belt" by Browning (1990) and Carlson (1991), and storms associated with these events are frequently referred to as "Pineapple Express" events because of their origins in the tropics (Higgins et al. 2000).

Most of our information about the moisture associated with AR's over the open ocean come from polar orbiting satellites equipped with microwave radiometers. Section 4 presents the first direct evidence for the accuracy and reliability of TPW retrieved from these observations. **Figure 1** derived from the NOAA operational Blended TPW Product provides us with a view of a landfalling AR that impacted the Pacific Northwest early in December, 2010.

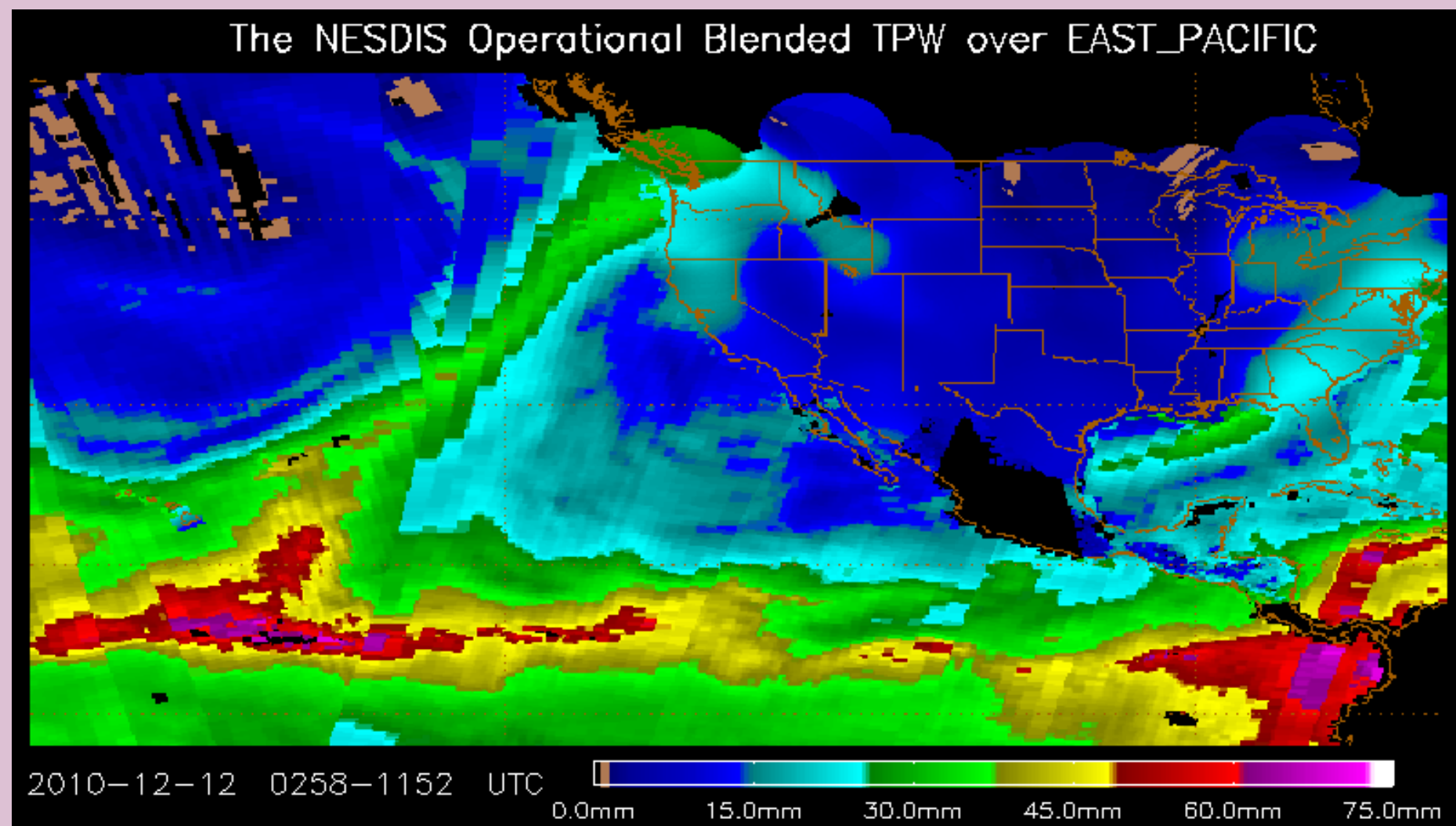


Fig 1. NOAA Operational Blended Total Precipitable Water (TPW) product originally developed for NESDIS by CIRA (Kidder and Jones, 2007) that is available to NWS forecasters on AWIPS workstations and the general public at <http://www.osdpd.noaa.gov/bTPW/>. The observations used to create this "on-the-fly" product are AMSU and SSM/I brightness temperatures offshore and GPS-Met observations (<http://gpsmet.noaa.gov/test/>) onshore. The blended TPW product allows forecasters to 1) monitor the evolution of AR's and 2) verify numerical weather prediction models to improve forecast lead time and prediction skill of heavy precipitation associated with these events.

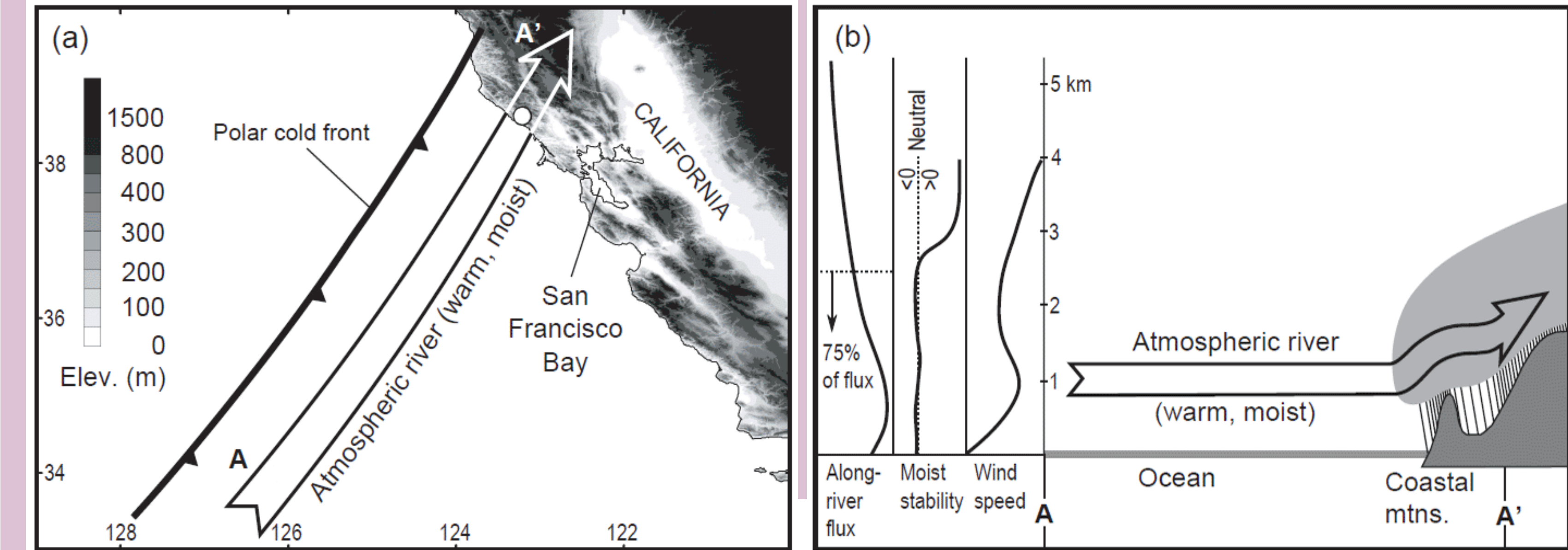


Fig 2. Representation of conditions in the atmospheric river region of a land-falling extratropical cyclone over the northeastern Pacific Ocean (modified from Neiman et al. 2009 and Ralph et al. 2005).

- (a) Plan-view schematic (left) showing the relative positions of an atmospheric river and polar cold front.
- (b) Cross-section schematic (right) highlighting the offshore vertical structure of wind speed, moist static stability, and along-river water vapor flux. Schematic orographic clouds and precipitation upon landfall are shown on the right, with the spacing between the rain streaks proportional to rain intensity.

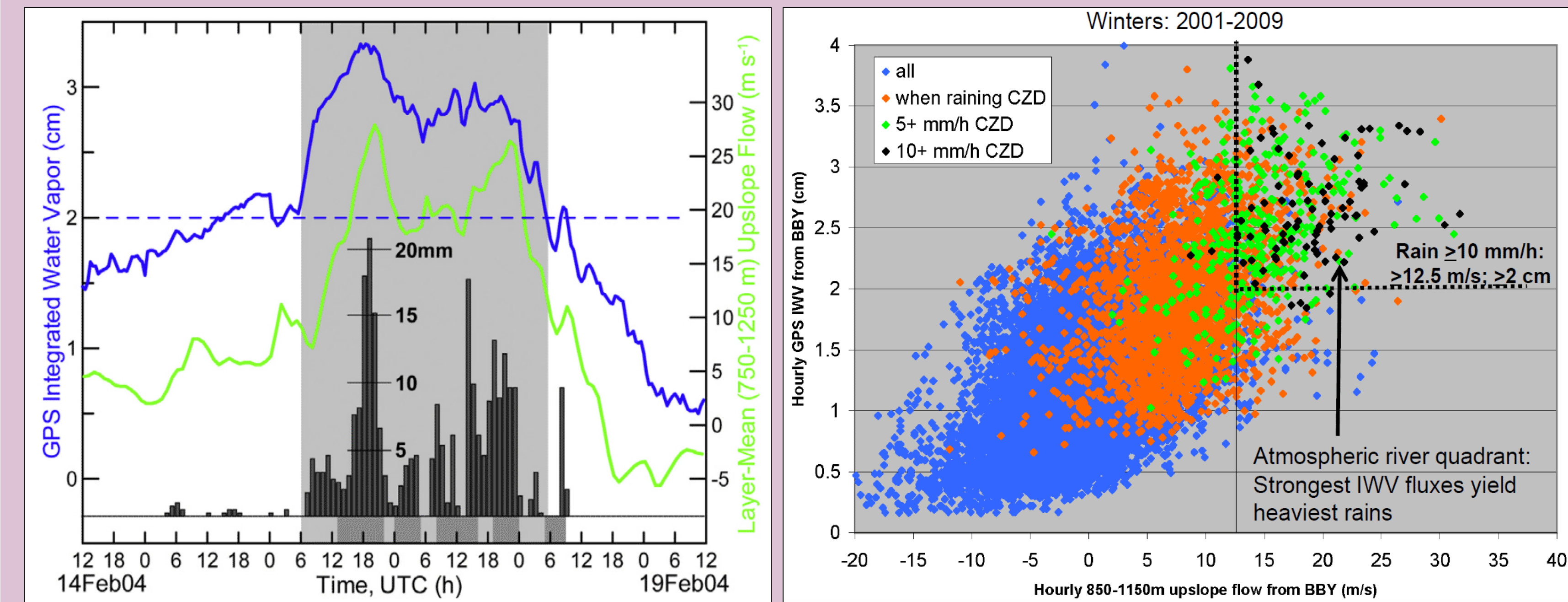


Fig 3. TPW time series in blue and layer-mean (750-1250 m MSL) upslope flow (in m-s⁻¹; green) at BBD, one of the AR Observatory sites described in Section 2. Black histogram denotes hourly rainfall during the AR event at a nearby site (CZD) between 14-19 February 2004. The light gray-shaded bar marks atmospheric river conditions where TPW > 2 cm.

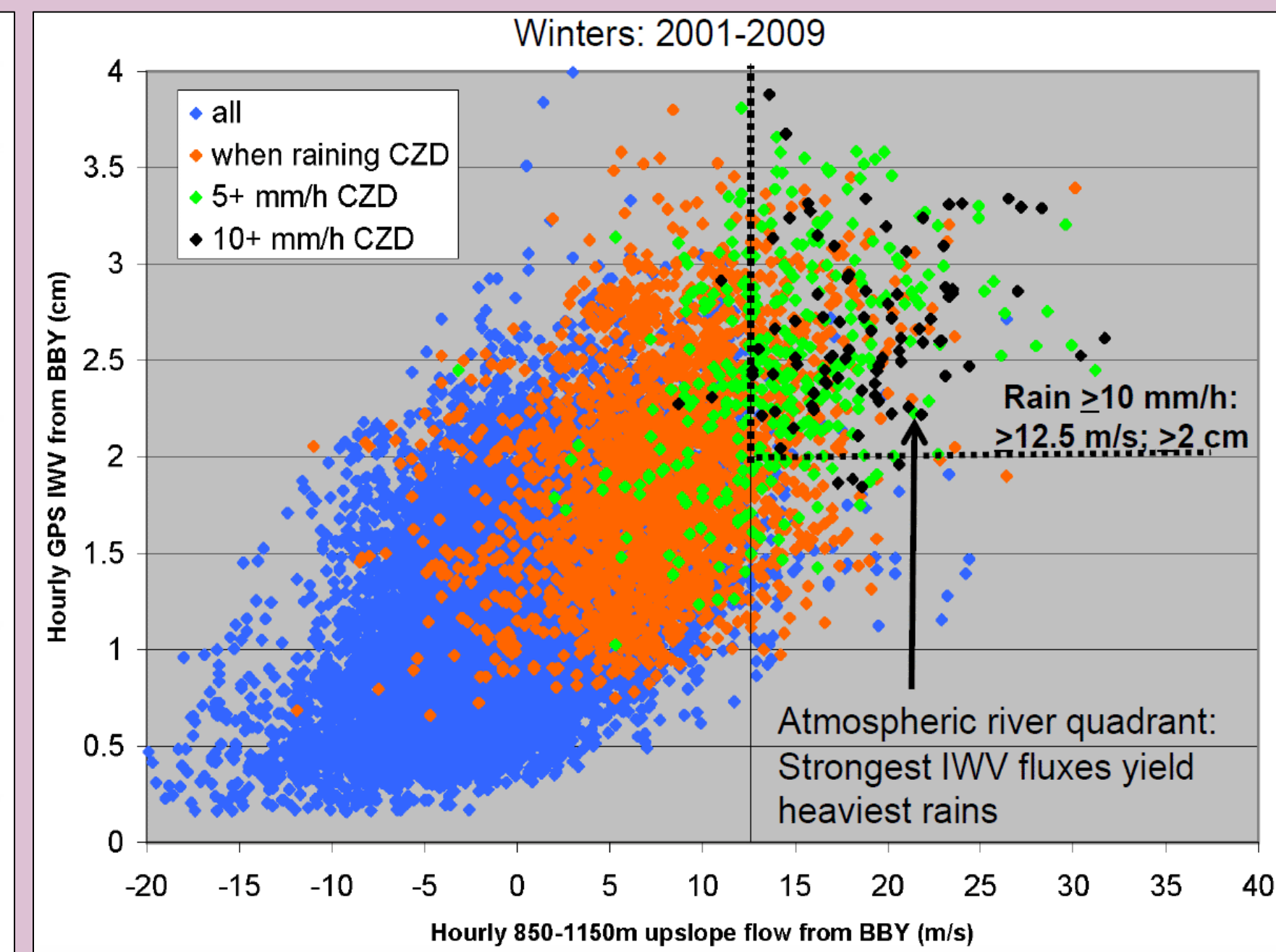
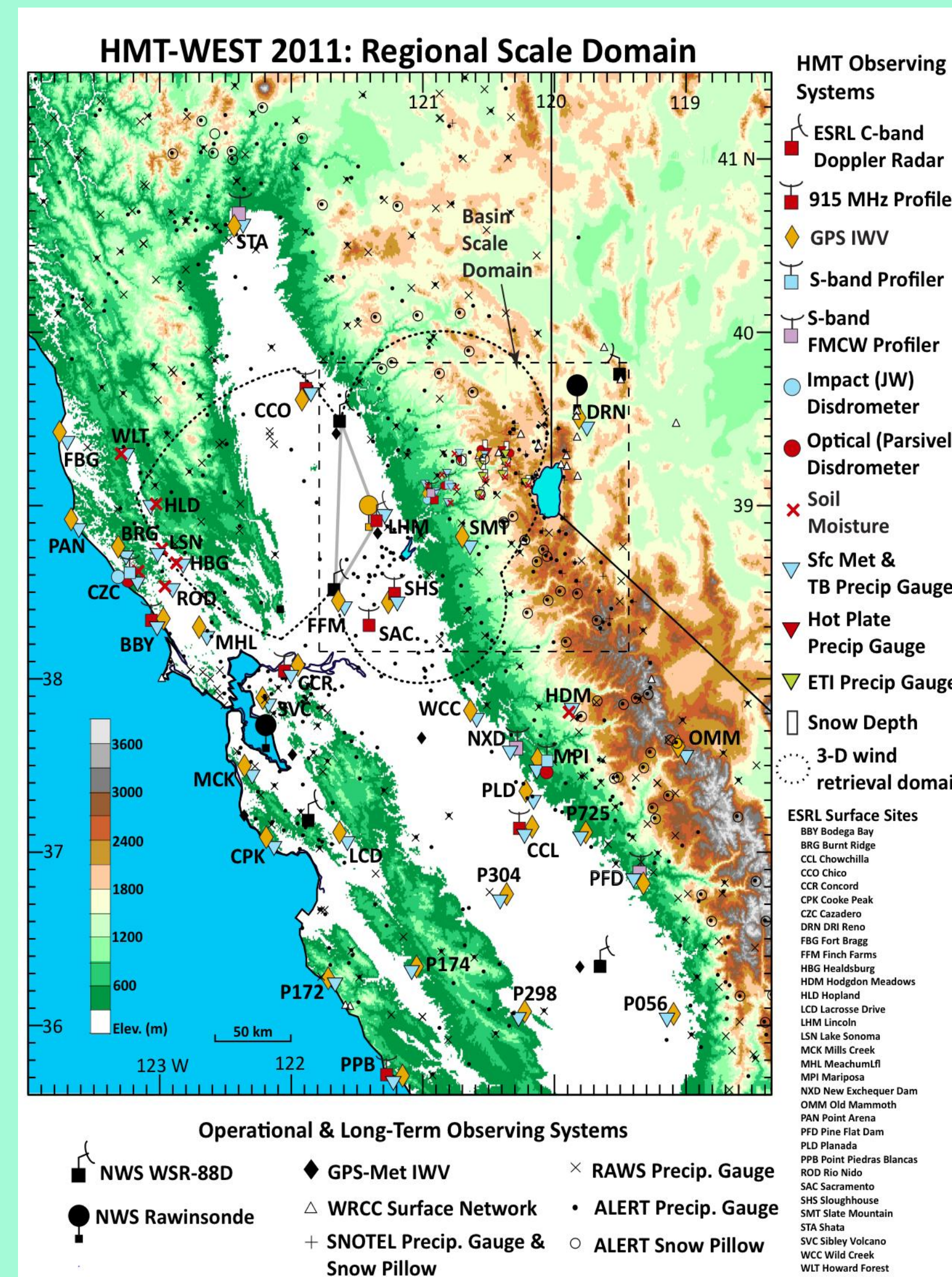


Fig 4. TPW (abscissa) versus upslope flow (m-s⁻¹) in the 850-1150m MSL layer (ordinate) for Winters: 2001-2009. The data used to create this plot came from 9-years of ground-based wind profiler and GPS-Met observations made at the Atmospheric River Observatory (ARO) sites near Bodega Bay, CA (BBY) and Cazadero, CA (CZD) described in Section 2.

2. Atmospheric River Observatories



- Key**
- 10 m meteorological tower
 - GPS-Met antenna
 - 915 mHz Doppler wind profiling radar
 - Vertically pointing S-Band profiler
 - Disdrometer and precipitation gauges.
 - Equipment trailer

The primary purpose of the ARO is to make direct real-time measurements of wind speed, direction, and moisture from which bulk moisture flux is calculated & displayed on forecaster workstations and assimilated into numerical weather prediction models.

Atmospheric River Observatories (ARO's) are facilities established by NOAA in collaboration with other state and federal government agencies and universities to monitor and improve forecasts and warnings of severe weather associated with landfalling AR's as described in Section 1.

Basically ARO's consists of an observing couplet: a coastal site where water vapor transport is measured and an inland site, usually located along the nearest inland terrain barrier, where the precipitation that falls is enhanced by orographic forcing is monitored. Coastal sites contain a Doppler wind profiling radar, a Global Positioning System water vapor unit (GPS-Met), and a surface meteorological tower. Inland sites usually contain a vertically pointing S-band precipitation profiler, a raindrop disdrometer, and a surface meteorological tower. The ARO installed near Westport, WA illustrated in **Figure 5** below contains all of the instruments identified above.

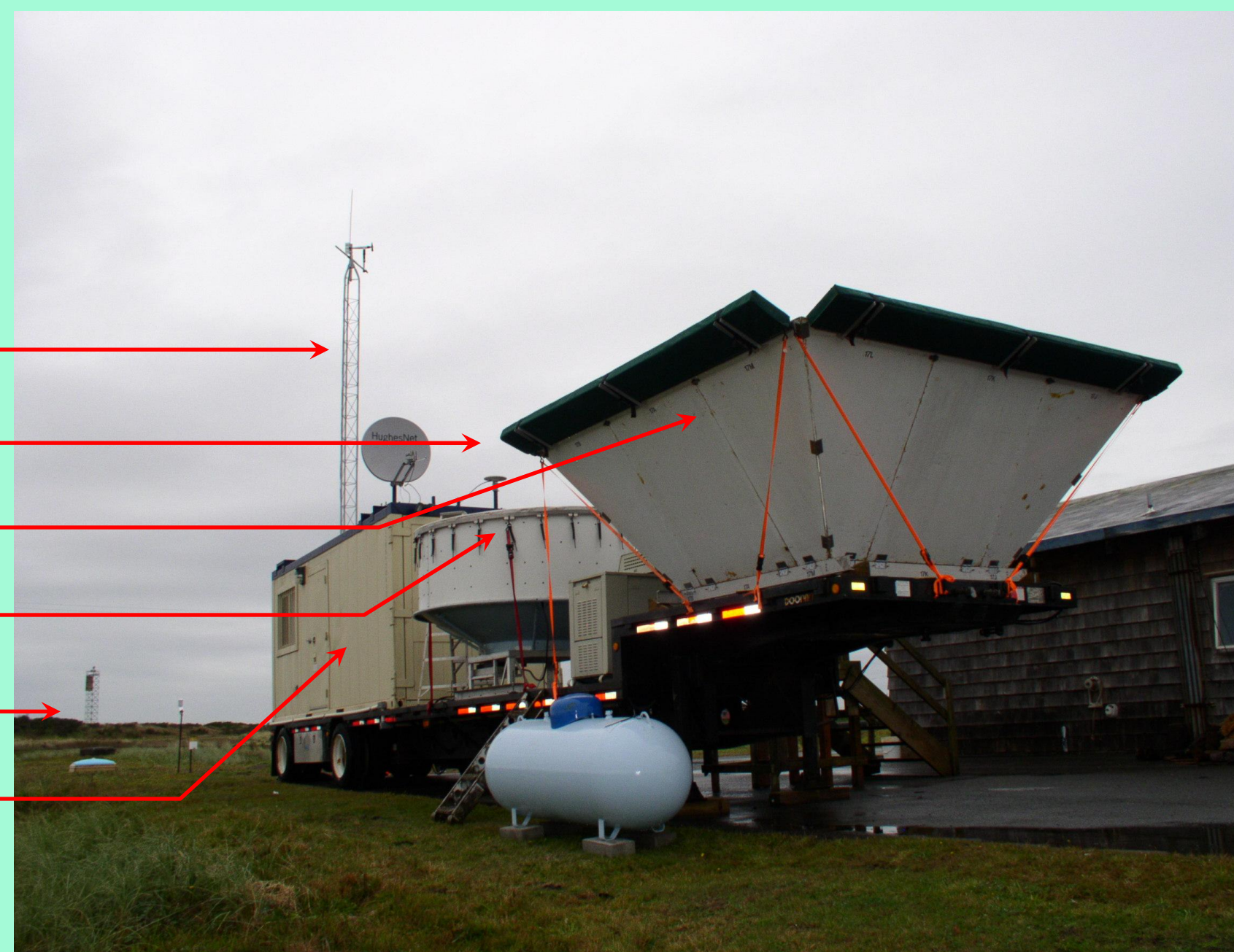


Fig 5. Atmospheric River Observatory located near Westport, WA at Westport, WA at Latitude: 46.906322 Longitude: -124.116408, Elevation: 3.8 m.

3. Moisture Flux

As observed in Figure 4 (left) there is an unambiguous relationship between rain rate, moisture, and wind velocity in the upslope direction associated with orographically-induced precipitation events. This relationship was defined by Alpert (1986) and the practical implementation of this in the form of a water vapor flux tool was described in Neiman et al., 2009.

Where: $RR = \text{rain rate}$

$$\overline{pq} = \text{the product of the layer-mean air density and the water vapor mixing ratio}$$
$$\vec{V} \cdot \nabla Z_s = \text{the horizontal wind velocity normal to the terrain at a height } Z_s \text{ above the topography.}$$

An example of the output from the water vapor flux tool is illustrated in **Figure 6**, and the analysis of these observations at high (9 km and 1-h) spatial and temporal resolution using LAPS, the ESRL GSD Local Analysis and Prediction System available at (http://laps.noaa.gov/cgi/laps/domains/psd/laps_a_nl_psd_umf_latest.cgi/) is presented in **Figure 7**.

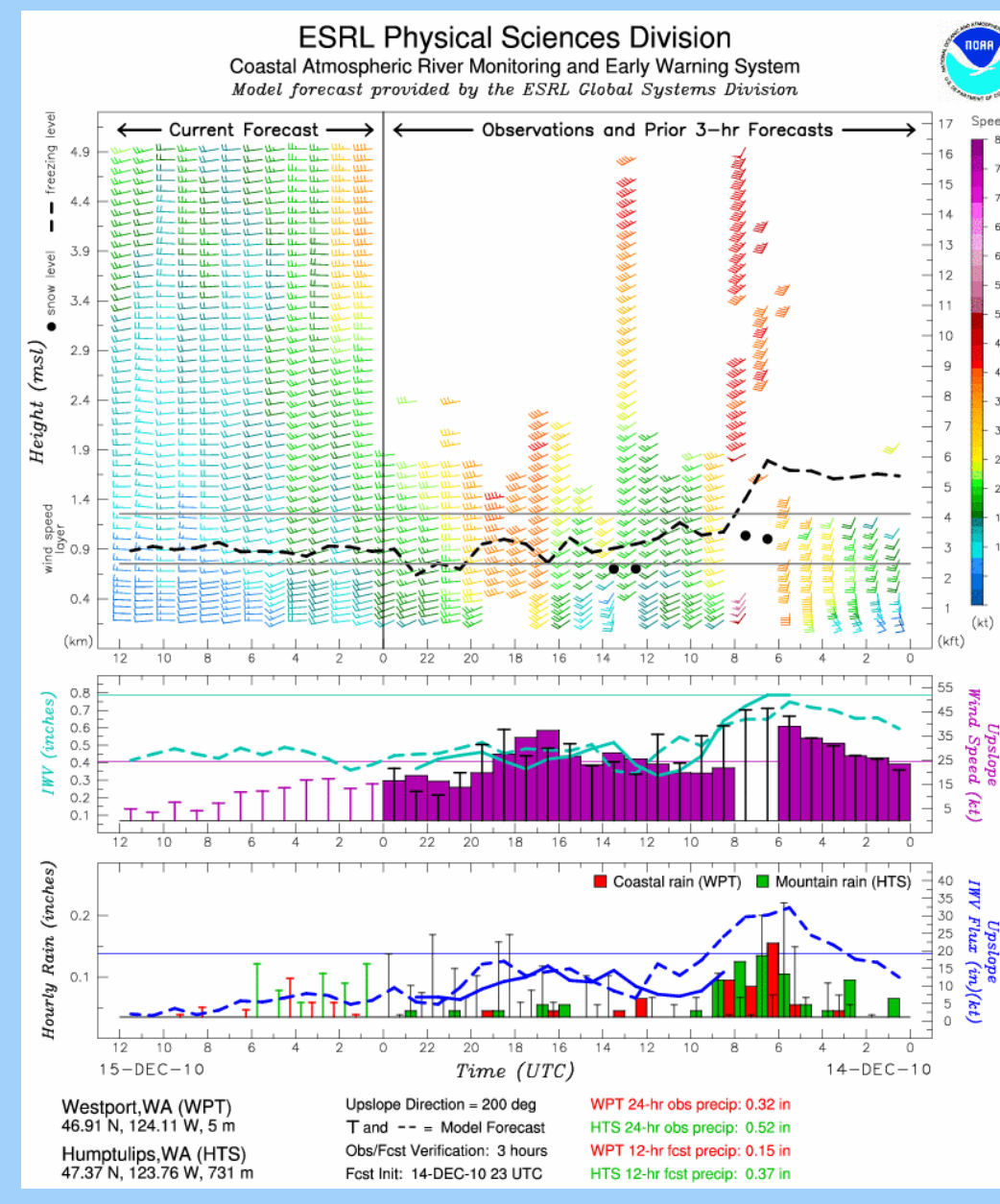


Fig 6. Water Vapor Flux Tool.

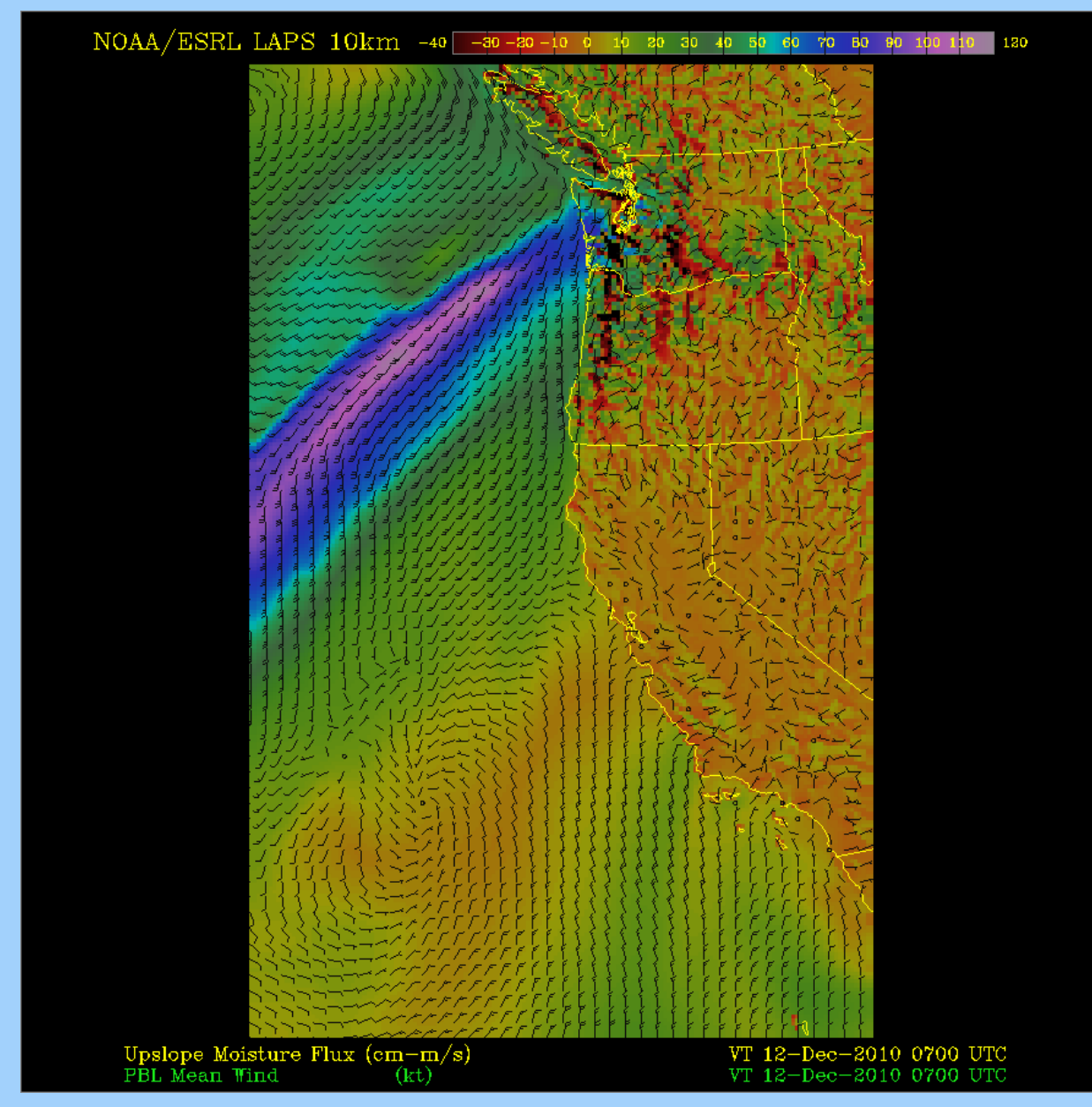


Fig 7. LAPS Analysis of UMF observations.

4. Satellite Microwave TPW Obs Offshore

4.1 Discussion

The passive microwave radiometers on polar orbiting spacecraft (e.g. AMSU on NOAA 18, 19 and MetOP-A AMSR-E on Aqua, etc.) receive and measure radiation emitted and scattered from the earth, ocean, cryosphere and atmosphere. The latter include the contributions from the molecular constituents of the atmosphere including water vapor, and clouds, precipitation, and aerosols. Over land, it is possible to verify the accuracy of geophysical parameters retrieved from observed radiances or estimated brightness temperatures by direct comparison with other remote sensing and in situ measurements such as radiosondes. Over the open ocean, away from the influence of contamination by the emissivity of the solid earth and land cover, this is extremely difficult to do except in "campaign mode."

4.2 Experimental Results

ESRL in collaboration with Devon Energy and the Apache Corporation, Louisiana State University Spatial Reference Center, Scripps Orbit and Permanent Array Center and UNAVCO established permanent GPS continuously operating reference stations on offshore platforms in the Gulf of Mexico. The purpose of this experiment is to evaluate the characteristics of TPW from eight microwave sounding systems onboard U.S. and European spacecraft in low Earth Orbit. **Figure 8** shows the platforms (right) and locations (left) of these sensors with respect to the continental U.S. **Figure 9a & b** present the results over 56 days this year.

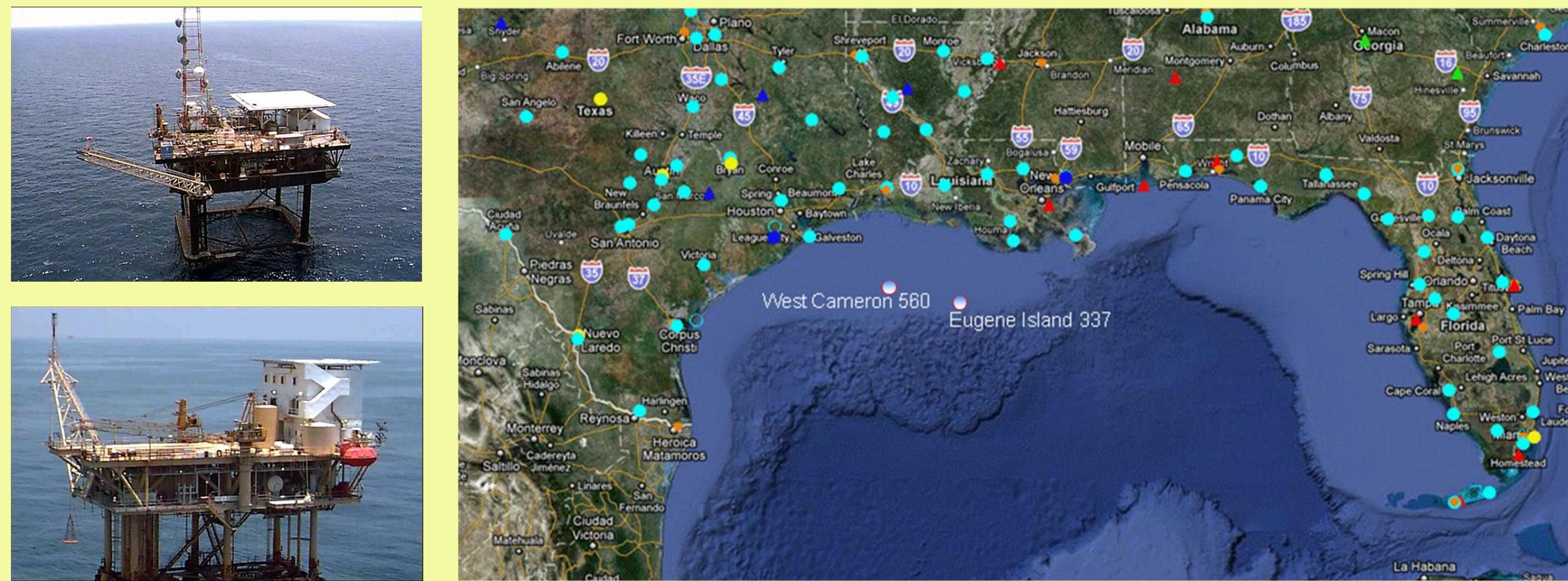


Fig 8. Apache Corporation Oil Platforms hosting NOAA GPS receivers. West Cameron 560 (DEV2; upper left) and Eugene Island 337 (DEV1; lower left) are both located about 140 km offshore and are separated by 145 km.

